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Performance of hospital spaces in summer

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Abstract: Most spaces in UK hospitals are heated and mechanically ventilated, with cooling restricted to specialist areas. In many cases, wards and associated circulation and administrative areas receive additional but limited natural ventilation through window openings. Such spaces account for 70% of the operational area of a typical hospital.

Glenfield Hospital comprises connected cruciform blocks with numerous small courtyards between. The hospital has mechanical ventilation and perimeter heating. The wards have a hybrid ventilation strategy with a low rate of mechanical ventilation. Ventilation through windows is the main source of summer time cooling. This paper investigates the summer time performance of spaces that are mechanically ventilated but passively cooled during summer. The paper presents the measured indoor temperatures in selected hospital spaces and compares them with thermal comfort criteria. Finally, future summer conditions for a typical ward space are predicted using a calibrated dynamic thermal model.

During the four month monitoring period, the maximum indoor temperatures in the case study spaces varied between 26.6 °C and 29.3 °C. Generally, the nurse stations were found to be the hottest areas. During this period the performance of most of the monitored spaces was reasonably within the thermal comfort threshold as defined by HTM03-01. The simulation results demonstrate that light-touch low carbon interventions could produce comfortable conditions in bedrooms into the 2050s.

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Energy and Building

Dear Prof Branislav Todorvic,

Please find attached our paper, 'Performance of hospital spaces in changing climate: A case study of 'Nucleus'-type hospital in the UK Midlands'. This is an output of EPSRC funded research project. We look forward to hearing from you in due course.

Thanking you.

Yours Truly,

Dr. R.Giridharan

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Performance of hospital spaces in changing climate: A case study of ‘Nucleus’-type hospital in the UK Midlands.

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be the hottest areas. During this period the performance of most of the monitored spaces was reasonably within the thermal comfort threshold as defined by HTM03-01. The simulation results demonstrate that light-touch low carbon interventions could produce comfortable conditions in bedrooms into the 2050s.

Keywords: summer; overheating; hospital; thermal comfort; natural ventilation; simulation; calibration; low carbon.

1. Introduction

The Design and Delivery of Robust Hospital Environments in a Changing Climate (DeDeRHECC) research project is investigating the impact of summer overheating in hospital campuses operated by four National Health Service (NHS) Acute Trusts. The sites under examination are: Addenbrooke's (Cambridge); Bradford Royal Infirmary; Glenfield Hospital (Leicester); and St Albans City Hospital. In each of these hospitals, 3 to 4 ward spaces in 2 or more buildings have been monitored since June 2010. Some of the findings and possible measures to adapt the Addenbrooke's and Bradford buildings to climate change have been presented elsewhere [1,2,3]. This paper discusses the performance of Glenfield Hospital.

Hospitals can experience overheating during the summer, especially when the outdoor temperature is more than 20°C. The degree and duration of overheating will depend on geographical location, building design, ventilation strategy and internal gains. Geographically, the Midlands are 80% rural and have a climate which is transitional between northern (cool

summer¹) and southern (warm summer) England. The historical climate data² for Leicester, covering the period between 1971 and 2000, shows that the summertime mean maximum and the mean temperature were in the region of 20.0 °C and 14.5 °C respectively [4]. Detailed analysis of 10 years hourly summer data³ prior to 2010 shows that only in 2003 were there 9 hours above 30 °C with a maximum temperature of 31.9 °C (Fig. 1). Generally, there were fewer than 90 hours over 25.0 °C in each summer, except for 2003 (97 hours) and 2006 (150 hours). In 2010 there were 36 hours over 25.0 °C with mean and maximum temperatures in the region of 14.3 °C and 27.3 °C respectively. When compared with all the summers of the last decade, it appears that the 2010 summer was mild. However even in a mild summer an inappropriate design strategy could lead to overheating, especially where cross ventilation is very poor and heat trapping is encouraged.

The Glenfield Hospital design, developed in the late 1970s, was based on the ‘Nucleus’ concept (Fig. 2). ‘Nucleus’ is the name given to a way of planning hospitals that was widespread in the UK between the late 1970s and the early 1990s; more than 100 whole ‘Nucleus’ hospitals or part-schemes were constructed [7,8]. ‘Nucleus’ was a template-based approach which accommodated hospital departments within a standardised cruciform floor area of 1000 m². These templates were laid out on one or both sides of a connecting corridor (the ‘street’) to a maximum of two storeys. In theory, any template could be placed above or alongside any other, creating a low-rise regular ‘mat plan’ [9] with numerous courtyards. The first and second phases of Glenfield Hospital were completed in 1984 and 1989 respectively; subsequently there have been various extensions. The building has two storeys with a flat roof. It features a steel frame with external brick facing. The first phase had single glazed timber windows, but these were later upgraded to double glazing. The second phase had

¹ This research considers 1st May to 30th September as summer.

² Information is extracted from the climate maps produced by the Meteorological office for the Midlands [4].

³ Cottesmore Meteorological Station, Oakham, Rutland, Leicestershire.

double glazing from the outset. One intended feature of the chequerboard layout was that areas could be naturally lit and ventilated from the courtyards where clinically appropriate [10].

All the clinical and patient areas are mechanically ventilated with perimeter heating. There are 25 air handling units (AHU) of varying size covering different parts of the hospital. Each of these AHU's is designed to cater for two or more wards. There are also exclusive AHU's for operating theatres and laboratories. The hot water for heating is supplied from the central plant, which has two gas combined heat and power (CHP) units and four gas boilers. On most occasions the hot water is generated through CHPs, but when there is a peak need, the boilers will start functioning in a sequence. In addition to operating theatres and laboratories, mechanical cooling is only provided to selected spaces such as drugs and treatment rooms in some wards. The principal cooling for the wards is by natural ventilation through window openings. There is a perception in the hospital, especially among the nurses, that the indoor environments are too hot in summer. This paper investigates the performance of naturally cooled spaces, especially wards, and simulates strategies to reduce overheating during future summers, which, due to climatic warming, are more likely to have periods of hotter summers.

2. Methodology

The 'DeDeRHECC' research team has developed a standard methodology to study the performance of the hospital environments [1]. Using a standard methodology enables the reader to compare the results for different hospitals within the context of the study. A brief description of the methodology is presented here. Firstly, representative recurring 'type' buildings are identified on case study sites and information on their geometry, construction, service strategy and environmental controls is sourced from construction drawings,

discussions with facilities managers, and field visits. Secondly, internal temperatures are monitored in selected representative spaces, with the exact choice of spaces for each building being made in consultation with ward staff and facilities managers. Thirdly, the downloaded data are cleaned and results are compared with the thermal comfort criteria described in Health Technical Memorandum 03-01⁴ [11], BSEN15251⁵ [12] and CIBSE⁶ Guide A [13]. Thresholds for these criteria are presented in Table 1. For a year, the HTM03-01 limiting value is 50 hours. The study assumes that indoor temperatures do not rise above 28°C outside the summer period (May to September). Therefore, 50 hours are assumed for the summer period. For any performance evaluation carried out for less than five months of the summer period, the HTM03-01 limiting value is adjusted proportionately for the corresponding period. For the monitoring period⁷ 1st June to 30th September, the threshold values for HTM03-01, BSEN15251 and CIBSE are 40, 147 and 12 hours respectively. Finally, a sample ward space is modelled using the IES dynamic thermal model [14]. Since the focus of the research project is overheating, the model is calibrated by comparing predicted with measured internal temperatures for the monitored period.

This paper limits the modelling work to a part of a typical ward and discusses the applicability and limitations. The weather data for modelling work were sourced from Cottesmore Meteorological station, located about 20 miles north-east of Leicester. This is the nearest meteorological station that provides all the data that are necessary to create simulation weather files. However, to analyse the summer 2010 monitored indoor temperatures, the outdoor temperature data from the Gateway⁸ weather station were used. The simulation

⁴ Hours over 28° C.

⁵ Adaptive criteria.

⁶ Night time sleeping condition.

⁷ Total number of hours: 2928. Total number of night time (21:00 to 6:00) hours: 1220.

⁸ The Gateway weather station is located at DeMontfort University, Leicester.

weather files for the year 2010 (Cottesmore⁹), current¹⁰ (Cottesmore) and future (Leicester) probabilistic weather files were created by the 'Prometheus' research team at Exeter University. The future probabilistic weather files were derived using UKCP09 data [16]. A detailed account of this process has been presented elsewhere [1].

3. Case study description

At Glenfield Hospital there are 18 wards. The monitoring scope was limited to Wards 18, 19, 27, and 32, and the main waiting area (Figs. 3, 4, 5, 6 & 7). These spaces were selected considering their accessibility and also limitations imposed by the infection control department of the hospital. Wards 18 and 19 are on the ground floor and are part of the first phase. Wards 27 and 32 are on the first floor and are part of the second phase. The waiting area is part of the second phase and is located on the ground floor. Wards 18 and 19 are on the West-East axis while Wards 27 and 32 are on the South-North axis. Each of the Wards 18 and 19 accounts for a floor area of 1300 m² whilst each of 27 and 32 account for 1200 m². The floor areas under investigation in wards 18, 19, 27 and 32 are 270 m², 290 m², 216 m² and 285 m² respectively. The main waiting area is approximately 95 m².

The external walls of the wards are 300mm thick with 50mm insulation (U-value=0.4 W/m²K). The roof is made of a 300mm in-situ RCC slab with 87mm insulation above (U-value=0.26 W/m²K). Generally the window openings in the wards are of three types and they are 1600mm×1800mm, 1600mm×900mm or 800mm×900mm. All the windows are double glazed (U-value=1.9 W/m²K) and top hung (operable windows). The window opening is

⁹ Comparison of the 2010 summer time outdoor temperature at Gateway and Cottesmore weather stations show a reasonable match. The maximum temperatures at Cottesmore and Gateway were 27.3 °C and 27.0 °C respectively while the mean temperatures were 14.3 °C and 15.1 °C respectively. The hours over 25.0 °C for Cottesmore and Gateway were 36 and 46 respectively.

¹⁰ Current TRY is based on 1984 to 2004 weather data while the current DSY is 2004. Refer Levermore and Parkinson [15] for the method.

restricted to 100mm for patient safety [17]. The floor to floor height and floor to ceiling height are 3.9 m and 2.7 m respectively.

Fresh air is heated¹¹ to 18 °C and supplied to spaces. In Wards 18 and 19, the area containing the bed bays and nurse station has two supply grilles, which are located on the corridor ceiling closer to the nurse station. In ward 27, the study area has one supply grille, located on the nurse station ceiling. The air flow rate in Wards 18, 19 and 27 for the area under study are 164 l/s, 164 l/s and 135 l/s respectively [18]. Furthermore, though there are additional supply grilles in the corridors leading to bed bay areas of Wards 18, 19 and 27, they mainly ventilate the administrative and service spaces located along these corridors. In Ward 32, it is difficult to zone the ventilation system. Unlike the other three wards, there is a supply grille in one of the multi-bed rooms. Otherwise the supply is fairly spread in the corridor and other service spaces. The supply rate for the whole Ward 32 is 1390 l/s. Considering the internal floor area of 1040 m² (2808 m³), ward 32 has a supply rate of 1.8 ach⁻¹ while Wards 18, 19 and 27 receive 0.8, 0.8 and 1.2 ach⁻¹ respectively for the area under investigation. The slightly higher air change rate for Ward 32 could be attributed to the location of the ward within the overall layout i.e. all the external facades of the Ward 32 face an internal¹² courtyard with possibly resulting low ventilation through window openings (Fig.2). It is important to note that the mechanical ventilation in these wards is well below the current HTM03 guidance of 6ach⁻¹, though there is some supplementary flow of air through windows (though these are restricted to 100mm opening for perceived patient safety). It was noticed that windows were kept open even when the outdoor temperature was around 10 °C. The bed bay areas and nurse stations do not have any extract facility, but the toilets and the treatment rooms are connected to extract systems. There are separate clean and dirty air extract systems. The air extracted from

¹¹ When the outdoor temperature is greater than or equal to 18 °C, the mechanically supplied air is not heated.

¹² Wind velocity in the internal courtyard will be much lower than what is prevailing in an un-trapped open area in the same location.

the toilets is considered dirty while the air from treatment spaces and meeting rooms is clean. Thus a substantial part (75%) of the supplied air to the ward is being extracted through these spaces in Wards 27 and 32. The balance of the air in these wards escapes through the windows. However, in Wards 18 and 19 the bulk (80%) of the supplied air leaks through windows.

The wards have a perimeter heating system. There are hot water loops running around each courtyard. Each loop is connected to a separate heat exchanger. The hot water to these heat exchangers comes from the central CHP-cum-boiler plant. The hot water to perimeter heaters comes from the loop that is running in the adjacent courtyard i.e. one ward gets hot water for heating from more than one loop, because each ward is bounded by more than one courtyard. The temperature of the hot water in these loops is regulated¹³ by thermostats in relation to outdoor temperature. In the bed bay areas, especially in single bed rooms, it is possible to control the radiator through 'on/off' valves.

4. Performance of monitored spaces: June to September 2010

There were 7, 6, 7, 12 and 4 hobo loggers in Wards 18, 19, 27, 32 and the waiting area respectively (Figs. 3, 4, 5, 6 & 7). The research team has been monitoring the hourly internal temperature using Hobo loggers continuously since June 2010 but this paper will present the results covering the period 1st June to 30th September 2010 (2928 hours). During this period two loggers were lost, one each in Ward 32 and the waiting area. All loggers were placed away from direct sunlight. They were cleaned at the time of each installation and prior to the downloading of data by a person assigned by the infection control department using alcohol-based cleaning tissues. Only this person was allowed to place and remove the loggers on the

¹³ Supply water is 70 °C when $T_{out} \leq -3$ °C then it ramps down to 20 °C when $T_{out} \geq 20$ °C.

hooks attached to the wall. Once every three months, data were downloaded to avoid loss of data/loggers. The research team member downloads the data and relaunches the loggers, and hands them back to the hospital employee for installation. The summary of the performance of Wards 18, 19, 27, 32 and waiting area during the summer of 2010 is presented in Table 1.

Among the case study spaces, the maximum temperature of 29.3 °C was observed on 30th June in the space 2W27-SB2 when the outdoor temperature was 24.3 °C. During the study period, the maximum outdoor temperature of 26.9 °C was recorded on 27th June, however on that day 2W27-SB2 recorded 28.3 °C. There thus appeared to be a lag of three days between the outdoor maximum and the subsequent internal maximum being reached in 2W27-SB2. However, 2W27-SB2 demonstrates unusual performance (discussed below), so the above finding should be viewed cautiously. Among the bedrooms, the second-maximum temperature of 28.4 °C was recorded in 2W27-MB1 on 29th June when the outdoor temperature was 23.9 °C. This space shows a lag of two days. In general, all spaces in wards 19, 27, 32 and the waiting area reached the maximum between 27th and 30th June¹⁴. 1W18-22OW recorded its maximum temperature of 26.6 °C on 10th July when the outdoor temperature¹⁵ was 26.1 °C. Both 1W18-22OW and 1W19-24OW have similar long south facing facades, but 1W18-22OW façade is reasonably shaded by the adjacent children indoor play area (Fig. 2). Therefore 1W18-22OW would be expected to have a lower temperature than 1W19-24OW on that day. However, on that day 1W19-24OW recorded a maximum temperature of 26.1 which is 0.5 °C lower than 1W18-22OW. In contrast, when 1W19-24OW recorded the maximum temperature of 26.8 °C on 27th June, 1W18-22OW recorded 26.1 °C (difference of 0.7 °C). Since the construction details¹⁶ and service strategy are the same, it

¹⁴ Most of the spaces reach their peak temperature within a few hours of the outdoor peak.

¹⁵ 8th maximum outdoor temperature.

¹⁶ 1W19-24OW floor area is 20m² more than 1W18-22OW.

appears that there were other internal factors influencing the indoor maximum temperature in some spaces – for example window opening or occupancy level or internal gains.

The maximum internal¹⁷ diurnal temperature range of 6.2 K was recorded in 2W27-MB1 on 4th July when the outdoor maximum and minimum temperatures were 21.5 °C and 12.1 °C respectively. All the other spaces recorded maximum internal diurnal temperature ranges between 2.8 K and 5.0 K. However, different spaces recorded the maximum internal diurnal temperature ranges on different days even within the same ward. For example, 2W32-4MB1 recorded the maximum diurnal temperature range on the 4th June while 2W32-4MB3 recorded it on the 14th June. Furthermore, within the study period, the first diurnal maximum range occurred on the 4th June in 2W32-4MB1 and last on the 1st September in 2W32-SB1. However, during the study period, the maximum outdoor diurnal temperature range of 14.7 K was recorded on the 4th June¹⁸. Generally, the internal maximum diurnal temperature range occurred when the outdoor daily maximum temperatures were above 20.0 °C. However, there were three spaces; 2W32-SB2, 2W32-4MB3 and waiting area, recorded the internal diurnal maximum when the outdoor daily maximum temperatures were in the range of 12.0 °C to 15.7 °C. The occurrence of maximum internal diurnal temperatures on different climatic condition days and differences in maximum diurnal temperature within the same ward might be directly attributed to outdoor temperature of that day, degree and duration of window¹⁹ opening. This argument is further strengthened by the occurrences of minimum temperatures. The minimum indoor temperature of 18.2 °C was recorded in 2W27-SB2 on 15th July (01:00 hrs) when the outdoor temperature was 14.7 °C. However, on 17th July (00:00 hrs) when outdoor temperature was identical to that on the 15th July (01:00 hrs), the indoor temperature of 2W27-SB2 was much higher, 23.2 °C.

¹⁷ Internal maximum and minimum temperature on that day were 26.4 °C and 20.2 °C respectively.

¹⁸ Daily maximum and minimum outdoor temperature on that day were 25.3 °C and 14.7 °C respectively.

¹⁹ In the case of the waiting area, the main door opening.

1 The waiting area, 1W18-22OW and 1W19-24OW satisfy all three overheating and comfort
2 criteria. The comfortable conditions in the waiting area could be attributed to a very high
3 level of infiltration through the automatic doors. At the same time, in 1W18-22OW and
4 1W19-24OW it could be largely due to good cross ventilation. Among the single bedrooms,
5 only 2W27-SB1 met the BSEN15251 Cat I threshold. However, all the single bedrooms met
6 the HTM03-01 and BSEN15251 Cat II threshold except 2W27-SB2. The single bedroom
7 2W27-SB2 marginally exceeded the HTM03-01 threshold. In contrast, 2W27-SB1, 2W27-
8 SB2, 2W32-SB1 and 2W32-SB2 exceeded the CIBSE threshold, although 2W27-SB1's
9 exceedance of CIBSE threshold was relatively marginal²⁰.
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22 All the multibed rooms met the HTM03-01 and BSEN15251 Cat I II criteria. In contrast, all
23 the multibed rooms exceeded BSEN15251 Cat I threshold. However the exceedance in
24 2W32-4MB2 was marginal. All the multibed rooms exceeded the CIBSE threshold. All the
25 single bedrooms also experienced night time overheating. It appears that night time
26 overheating contributed to the exceedance of BSEN15251 Cat I in bedrooms, especially in
27 2W32-4MB3 (Fig. 8)²¹. In the wards, when the outdoor air temperature exceeded 18 °C, fresh
28 air was supplied without heating. During the monitoring period, there were 91 night time
29 hours over 18 °C. Further, whenever there were a few hours during the night in excess of 18
30 °C, the maximum day-time temperatures on that day and during the preceding days were in
31 the region of 23 °C to 26 °C. This daytime heat gets stored in the fabric. As a result, the
32 eventual supplied air to the wards could have been further a few °C higher since the supply
33 ducts pick up heat from the fabric. Therefore, for 91 hours, the wards could have been
34 continuously warmed to a higher temperature at night even if the perimeter heaters were
35 turned off. During this period, if the windows were kept closed, the problem could have been
36 aggravated further. The results indicate that windows were kept closed or partially closed for
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59 ²⁰ Refer to Table 2 notes for detail.

60 ²¹ A similar trend was observed in other multibed rooms.
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1 much of the warm nights. The above factors could have resulted in the exceedance of CIBSE
2 threshold. The impact of the climatic condition of the day, duration and degree of window
3 opening is discussed further in the modelling and calibration section.
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8 Generally, the nurse stations were the hottest areas. All the nurse stations met the HTM03-01
9 threshold except 2W27-NS. 1W18-NS²² exceeded BSEN1521 Cat I. The nurse station in
10 Ward 27 functioned as a heat sink, because, after use, all the medical equipment, including
11 the machines used for special treatment, light therapy etc are stored here for quick access. At
12 times, in the nurse station, equipment was left connected to power and kept in standby mode
13 to be used when the need arose. As a result, heat from the equipment slowly dissipated into
14 the nurse station. This is not standard practice but was observed on visits to this ward. Further,
15 the nurse station also houses non-medical equipment such as two computers, a photocopier
16 and printer. The heat released from this equipment might also have contributed to the
17 overheating of the nurse station. At 1W18-NS, the logger²³ was slightly closer to a printer.
18 The heat from the printer might have influenced the temperature recordings, especially in the
19 night. This contextual influence might have caused 1W18-NS to exceed the BSEN15251 Cat
20 I threshold.
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40 Overall it appears that Ward 27 had a relatively uncomfortable environment. The area under
41 study in Ward 27 encompasses a typical arrangement in a part of a cruciform ('Nucleus')
42 template (Fig.5). In the original plan there were no single rooms in this part of Ward 27.
43 There was a five-bed open bay instead of single bedrooms. The nurse station was an open
44 island and there were two multi-bed rooms with six beds in each. Ward 27 was refurbished in
45 2009 to create two single bedrooms. As a result the nurse station became an enclosed space
46 with openings towards the corridor. This new arrangement could theoretically have changed
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58 ²² Only nurse stations in open ward could be subjected to BSEN15251 since they are open islands.

59 ²³ This logger was connected to a CO₂ sensor which needed power. It was plug to a power socket that was next
60 to the printer power socket.
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the ventilation flow pattern and enhanced the heat trapping tendency. However, in reality, refurbishment is not the cause for the high temperature in 2W27-SB2. The single bedroom 2W27-SB1 is similar to 2W27-SB2 in terms of service strategy, construction and geometry, but it had very comfortable conditions during summer 2010. The internal temperatures recorded in 2W27-SB1 and 2W27-SB2 are presented in Figs 9 and 10 respectively along with outdoor temperature, its running mean and solar radiation intensity. It appears that 2W27-SB2 (Fig. 10) encountered additional heat gains compared to 2W27-SB1 (Fig. 9), especially between 22nd June and 2nd July. All 70 hours above 28 °C in 2W27-SB2 occurred during this period. The outdoor temperature during this period was between 26.9 and 10 °C with a mean of 18 °C. The outdoor temperature reflects a warm period. Therefore, overheating could have occurred if the room radiator was kept 'on' continuously during the warm period or if there was a large amount of medical equipment present. In discussions with the Facility Manager it was suggested that the first reason was the likely cause. Further, if the patient kept the windows closed, heat could also have been trapped. In this respect, the trend of 2W27-SB2 (Fig. 10) was in line with 2W27-SB1 (Fig. 9) after 2nd July. This is an indication that the results could be traced to the preferences of an individual patient; however, it is beyond the scope of this paper to investigate the reason that this particular patient preferred a high indoor temperature, or whether indeed the patient made a conscious choice of this kind. Overall, the monitored results indicate that as the wards become more open with substantial window area for cross ventilation, the possibility of meeting all three criteria are high, especially when the wards are dependent on natural ventilation through windows for summer time cooling.

5. Modelling and calibration

To predict the likely temperatures as the climate changes, a multi-zone thermal dynamic model of Ward 27 was constructed. The ward was chosen because of its relatively high level of overheating (see section 4) and as a case study to demonstrate the effect of subdividing a previously open ward. The study area of Ward 27 also represents to a great extent the internal layout of most of the nucleus type wards. The construction and general service strategies are as indicated above (see section 3). Fig.11 and Table 3 present the geometry and characteristics of the model respectively. In addition to spaces mentioned in Table 3, the model has five toilets and two storerooms. The extract system works through these spaces.

In the calibration process priority was given to achieve reasonably close alignment between measured and predicted hours over 28 °C [1,3]. The calibration was carried out by focusing on three spaces; 2W27-SB1, 2W27-MB1 and 2W27-NS. The single bedroom 2W27-SB2 was not considered for the calibration exercise since this space had unusual heat gains for a short period, as discussed in section 4. If the set points and internal heat gain profiles are adjusted to achieve this short period alignment, then the model overestimates the prediction for this space for the entire period (1st June to 30th September 2010). The changes in this room also influence the results of other spaces, especially 2W27-NS and 2W27-CD. Further, monitored data covering the period between May 2011 and September 2011 (3762 hours) showed that both 2W27-SB1 and 2W27-SB2 had zero hours over 28 °C. Therefore it is reasonable to assume both 2W27-SB1 and 2W27-SB2 have similar conditions and avoid tuning the model to achieve 2W27-SB2 results of 2010.

Sensitivity analysis was carried out to identify the critical variables necessary to tune the model. The model is sensitive to internal gains in the nurse station, especially heat gains from the equipment, the degree and duration of window openings in all the bedrooms and the

degree and duration of door opening²⁴ in single bedrooms. During day and night, the model assumed maximum occupancy gain at the nurse station as 29.7 W/m² and 23.6 W/m² respectively. Further, maximum equipment and lighting gains were set as 33 W/m² and 3 W/m² respectively. The model also assumed day and night staff²⁵ strength at the nurse station as 100% and 75% respectively. In a real situation, there could have been hours where equipment gains were very minimal due to non-usage or non-storage of heat-radiating medical equipment.

The opening and closing of single bedroom doors determines the level of cross ventilation i.e. the air flow between single and multi-bed rooms. The model shows that if the single bed room doors are kept closed continuously, the indoor temperatures, especially at the nurse station, and the number of hours over 28 °C in all the spaces, increase rapidly. Considering the above issue, the model assumed that during daytime the single room doors were kept fully open. At night, in any one hour, 50% of the doors were opened for five minutes. In real situation there could have been hours where the doors were kept closed for substantial parts of the daytime and open for longer durations during the night.

The window opening regime (Table 3) is one of the most uncertain assumptions but is very critical, especially in making night time predictions. The model cannot accurately reflect an individual's preferences i.e. the window opening regime will not change in line with each and every occupant decision. In the real situation, there could have been more hours where windows were closed or partially closed. Furthermore, all the rooms have more than one window. In the real situation, the degree and duration of opening of each of these windows could vary from room to room as well as within the room. In the model, all the windows

²⁴ The degree and duration of door opening in single bedrooms determines the level of cross ventilation.

²⁵ Maximum staff members at nurse station were 6. In addition, between 7:00 and 9:00, and 18:00 and 20:00 at every hour there were two staff members at each of the multi bedroom and one staff member at each of the single bedrooms for five minutes. The rest of the time at every hour there was one staff member at each of the single and multi-bedrooms.

1 follow the same opening profile. This could be corrected by creating window opening
2 profiles that reflect the changes in relation to time, space or quasi-random decisions.
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4 However, such an exercise requires considerable time and resources, and most importantly
5 information from clinical staff on occupancy. Nonetheless, in calibration, the predicted data
6
7 should have a good fit with the measured data over an array of reasonably accurate operating
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9 conditions [19]. Therefore, the model used a generalised window opening profile that
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11 reasonably reflects the overall trend in the ward (Table 3).
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18 Figs. 12, 13 and 14 present the scatter plot of measured and predicted dry bulb temperatures
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20 of 2W27-SB1, 2W27-MB1 and 2W27-NS respectively. Experiments have shown that the
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22 largest difference between measured data and predictions occur during periods of high solar
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24 radiation intensity (solar gain) and high air flow rate [19]. On most occasions, in bedrooms,
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26 during periods of high solar radiation intensity, the predicted temperatures were high
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28 compared to those measured (Figs.15 & 16). A similar trend was observed in nurse station.
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30 However, the deviation is marginal (Fig.14) in the nurse station due to relatively low solar
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32 gain (internal space). The deviations during high solar radiation intensity could be attributed
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34 to the weather file used for the simulation i.e. in real situation; solar radiation intensity could
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36 have been less than that in the Cottesmore simulation weather file. Furthermore, the model
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38 does not take into account the shading of the adjacent wings of the Nucleus building. Overall
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40 the deviations of the predicted temperatures during high solar radiation intensity are not
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42 significant²⁶. The modelled ward has a mechanical ventilation rate of 1.2ach^{-1} , which is very
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44 low. Therefore, the model-predicted temperatures were not very sensitive to mechanical
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46 ventilation but were sensitive to high natural ventilation through windows. The model
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48 overestimates the minimum temperatures in all the spaces. This overestimation of the
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50 predictions could be linked to the above-discussed window and door opening regime i.e. the
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60 ²⁶ Maximum deviation is 1.8°C.
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occasional 100% (100mm) opening of the windows during periods of lower outdoor temperature and/or the longer duration of single bedroom doors opened at night. However, the overall trends of the lower boundary of predicted and measured temperature of both the bedrooms are similar (Figs. 12 & 13). Similarly, there are occasions when the outdoor temperature is between 10° C and 20° C predicted temperatures of the bedrooms are low (Figs. 15 & 16). This has particularly caused an underestimation in terms of night-time overheating. During this period the model assumed that the windows were at least 50% (50mm) opened. However, in the real situation, there could have been less than 50% of the window opened, or some of the windows and doors could have been completely closed, resulting in high indoor temperatures. The deviations in the nurse station are due to changes in the internal gains (Fig. 14). The model assumes high equipment gains throughout but, in the real situation there could have been occasions when the equipment gain was less than or higher than what is assumed. Furthermore, the bottom boundary trend of predicted 2W27-NS (Fig. 14) resembles the bottom boundary trend of the bedrooms (Fig. 12 & 13), whereas the measured trend does not. This is because the predicted trend for the nurse station has been influenced by the heating regime of bedrooms. This could be corrected by increasing the modelling zones between the rooms and nurse station as well as in the rooms²⁷.

The predicted maximum temperatures of all the spaces were in good agreement with the measured values (Table 4). In overheating studies, the reliable prediction of peak temperatures is important [20]. The mean night-time temperature and hours over 28° C (HTM03-01 threshold) also show a good agreement with the measured values for all the spaces (Table 4). 2W27-SB1 shows marginal deviation in terms of CIBSE, and BSEN15251 Cat I and II while 2W27-MB1 shows relatively higher deviation in terms of CIBSE and

²⁷ The monitored data of 2W27-MB1 showed that at night the minimum temperature near the window varied between -1.3 to 1.9 K compared to near the corridor. But, for only 8 days in the total of 122 days was the temperature near the window was higher than that of near the corridor.

1 BSEN15251 Cat I. However these deviations do not change the overall thermal character of
2 the spaces. Furthermore, the model cannot capture the periodic intervention of the facility
3 managers to decrease or increase the heating provision (set point adjustment etc) at the
4 request of the ward staff. There were also periods when the single rooms were unoccupied
5 and multibed rooms were under-occupied. These changes will also influence the control of
6 radiators and window-opening, but this model cannot capture the impact of such changes.
7 There is further uncertainty in the assumptions relating to background infiltration²⁸ and the
8 air change rate between room and ceiling²⁹. These deviations are unavoidable considering the
9 complexity of the hospital environment, the scope and nature of the service strategies, and
10 regular changes in the patient's (occupant's) character. However, the predicted results for
11 summer 2010 indicate that the model deviation does not significantly change the overall
12 performance of the spaces (Table 5). All the spaces meet the HTM03-01 requirement. All
13 four bedrooms meet the BSEN15251 Cat I and II threshold. All but 2W27-6MB1 satisfy the
14 CIBSE night-time sleeping criteria.

37 38 **6. Predicted current and future performance**

39 Predictions were made by assuming that internal gains, occupancy character, window and
40 door opening strategy and services regimes remain unchanged for current as well for future
41 weather periods. In reality, there could be changes, and so the predicted results do not
42 indicate the optimal performance, but they do help to gauge relative performance of different
43 interventions. In addition, hospital services may not be upgraded for long periods of time.
44 The facilities managers have indicated that, since the completion of Glenfield in the 1980s,
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59 ²⁸ The model assumes background infiltration as 0.35ach⁻¹.

60 ²⁹ The air change rate between the rooms and void above the ceiling is assumed to be 0.75ach⁻¹.

1 there have been no major changes to service regimes except in Ward 27³⁰ (discussed below);
2 there have only been minor plant upgrades. Other research by the authors indicates that
3 central hospital plant may remain unchanged for forty years or more; ward refurbishments
4 tend to be relatively cosmetic and driven by an interest, understandably, in improving the
5 patient experience [3]. Where changes to ward layout are made, these tend to be relatively
6 minor.
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15 The construction of a new research complex started at Glenfield in late 2011. This building is
16 located on the western side of Ward 27 (Fig 2). In order to protect the ward from dust and
17 construction noise, an opaque barrier was erected. Furthermore, some of the windows were
18 sealed for a short period of time. As a result, the new project consultants as well as the
19 facilities managers decided to enhance the mechanical ventilation rate by 0.6 ach^{-1} (70 l/s)
20 temporarily. In order to gauge the impact of this change, the mechanical ventilation rate of
21 the calibrated model was changed to 205 l/s and the results predicted for summer 2010
22 (Appendix A). A major reduction is shown in the hours over 28°C in 2W27-NS. This
23 indicates that a slight increase in mechanical ventilation has the potential to reduce the impact
24 of internal gains. However, the predicted reduction in maximum, minimum and mean night
25 time temperatures were marginal for all the spaces as were the reductions in hours over for
26 CIBSE and BSEN15251 Cat I and II threshold.
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45 The thrust of the DeDerHECC research project is to test low carbon adaptive/refurbishment
46 measures as a way to improve thermal comfort in hospital buildings [1,2,3]. Light touch
47 measures are favoured by NHS Trusts, which are concerned about losing capacity for
48 extended periods of time and of the impact of construction on hospital function [3]. Therefore
49 this paper explores the impact of possible interventions on comfort without enhancing the
50 mechanical ventilation rate i.e. the mechanical ventilation rate was kept at 135 l/s . The paper
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60 ³⁰ Wards 27 and 26 are connected to a common AHU. Therefore change will affect the ward 26 as well.
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investigates the impact of: reducing internal gains at nurse station, horizontal shading above the windows and use of user controlled fans. These interventions are incrementally incorporated in to the model in three stages.

Considering the high internal heat gains at the nurse station, the **stage-1** intervention looks at the impact of lowering the internal heat gain to the range³¹ 33 W/m² to 44 W/m² by reducing the equipment maximum sensible heat gain (total) from 600 W to 200 W. This could be achieved to a large extent by using low heat-emitting and highly energy-efficient medical equipment in the future (though it could also be argued that there might be more equipment in the future) and by moving the non-medical equipment such as the photocopier/printer to a separate room away from the bed bays and nurse station. This intervention reduces the maximum temperature by approximately by 0.5 °C and achieves a very marginal reduction on mean temperatures. However, these reductions would significantly improve overall comfort level. **Stage-2** introduces a horizontal shading device above the windows in addition to the stage-1 conditions. The projection of the shading device is 1m while the thickness is 100mm. **Stage-3** adds to stage-2 a slow-moving fan. The fan becomes operational when the indoor temperature goes beyond 26 °C [1]. It is assumed that the fan moves to create an air speed of 0.3m/s and decreases the operative temperature by 1.2 °C [21]. The results presented here were achieved by post processing the stage-2 data i.e. 1.2 °C was deducted whenever the temperature exceeded 26 °C in stage- 2. The HTM03-01 threshold is not applicable to this option [1].

The predicted results for typical (TRY) and extreme (DSY) summer weather conditions are presented in Table 6. The results relating to HTM03-01, CIBSE and BSEN15251 criteria in Table 6 are left unshaded when results indicate that they are within the threshold limit, dark

³¹ In a day, the proposed internal gain fluctuates between 33 W/m² and 44 W/m². The fluctuation is largely due to changes in lighting requirement and occupancy level. For the existing internal gain level refer Table 3.

grey shade indicate where exceedance is substantial (could not be easily corrected by refining the window control strategy), and light grey shade where exceedance is minor (could be rectified by refined window control).

In the existing³² ward, during typical years, 2W27-SB1 is predicted to be comfortable both in terms of the HTM03-01 and BSEN15251 Cat 1 criteria up to 2030s. However, in terms of the BSEN15251 Cat II criterion, the space is comfortable right up to 2050s. The deviation in terms of the BSEN15251 Cat I criterion in 2050s is marginal. In terms of the CIBSE criterion, 2W27-SB1 is comfortable only under current (2005) condition. 2W27-6MB1 is comfortable in terms of the HTM03-1 and BSEN15251 Cat I criteria under current condition. However 2W27-6MB1 is comfortable right up to 2050s in terms of the BSEN15251 Cat II criterion. In terms of the CIBSE criterion, even under current conditions, 2W27-6MB1 is marginally uncomfortable. In terms of the HTM03-01 criterion, 2W27-NS is comfortable in 2005 but beyond that date it becomes uncomfortable. In extreme years, 2W27-SB1 becomes uncomfortable in terms of the HTM03-01, BSEN15251 Cat I and CIBSE criteria by the 2030s while it becomes marginally uncomfortable in terms of the BSEN15251 Cat II criteria by the 2050s. 2W27-6MB1 becomes uncomfortable in terms of the HTM03-01 and BSEN15251 Cat I criteria by the 2030s; however it becomes marginally uncomfortable in terms of BSEN15251 Cat II criterion by the 2030s. 2W27-NS is marginally uncomfortable even under current condition.

The above-mentioned staged interventions show gradual improvements in terms of the thermal comfort in each space. The improvements during typical years are substantial when compared to extreme years (Table 6). In typical years, all the way to the 2050s, in terms of the HTM03-01 criterion, 2W27-SB1 becomes completely comfortable after stage-2 while 2W27-6MB1 attains marginally uncomfortable, however, 2W27-6MB1 could be made

³² As per 2010 conditions of the ward.

comfortable after the stage-2 intervention by improving the window controls. In contrast, 2W27-NS is above the threshold even after the stage-2 intervention, however, after the stage-2 intervention, the overheating hours are reduced by 70% when compared to the existing condition. In terms of the CIBSE criterion, 2W27-SB1 becomes completely comfortable after stage-3 while 2W27-6MB1 reaches marginally uncomfortable status, however, 2W27-6MB1 could be made comfortable after stage-3 by improving the window controls. In terms of BSEN15251 Cat I, 2W27-SB1 and 2W27-6MB1 become completely comfortable after stage-1 and stage-2 respectively. In contrast, in terms of BSEN15251 Cat II without any interventions, 2W27-SB1 and 2W27-6MB1 are comfortable all the way to the 2050s.

In extreme years, all the way to the 2050s, in terms of the HTM03-01 criterion, none of the spaces will be comfortable even after all three stages of interventions. Similarly, in terms of the CIBSE criterion, 2W27-SB1 and 2W27-6MB1 will not be comfortable even after all three stages of intervention, but these two spaces have substantially fewer overheating hours (40%) after the stage-3 intervention. In terms of BSEN15251 Cat I, 2W27-SB1 and 2W27-6MB1 could achieve complete comfort after the stage-3 intervention; however, it is possible to make 2W27-SB1 completely comfortable after the stage-2 intervention by improving the window controls since the deviation is very marginal. In terms of BSEN15251 Cat II, 2W27-SB1 and 2W27-6MB1 become comfortable after stage-1 and stage-2 interventions respectively; however, it is possible to make 2W27-SB1 and 2W27-6MB1 comfortable with the existing condition and stage-1 interventions respectively by improving the window controls.

7. Discussion

It appears that the Midland climate might have had only marginal impact on the overheating of Glenfield Hospital's internal environments, especially during the last decade. During the

monitored period, the maximum indoor temperatures of the case study spaces varied between 26.6 °C and 29.3 °C while the minimum indoor temperatures varied between 18.2 °C and 22.2 °C. The maximum indoor diurnal temperature ranges between 2.8K and 5.0K and these ranges did not occur on the same day even within the same ward. The analysis of the monitored data and the modelling work showed that the degree and duration of window opening has a major impact on the occurrence of maximum diurnal temperature range on different days within the same ward. This has implications both in terms of comfort and energy consumptions [1,3]. It is good to have a large indoor diurnal temperature range on hot days since it helps to slow down the overheating process [2]. The data shows that a maximum diurnal temperature range of 4K or more with a minimum internal temperature of 20 °C could lead to comfortable conditions. In contrast, low indoor diurnal temperature range during hot days will accelerate overheating process. The dynamic thermal models were able to capture this trend. Furthermore, during calibration the model showed that overheating in one room could impact on adjacent rooms, especially when a space has a very low level of mechanical ventilation similar to that prevailing in Glenfield Hospital. It is important for the ward staff to be aware of this issue and manage the window-opening and the heat-radiating equipment during hot days.

During the monitored period, both open wards were comfortable in terms of all overheating and comfort criteria discussed in this paper. It appears in open wards that keeping the windows open on the opposite sides enhanced the cross ventilation. This has resulted in keeping the mean daytime and nighttime indoor temperatures around 23.0 °C. On the other hand, during this period, single and multibed bedrooms met the HTM03-01 and BSEN15251 Cat II thresholds except 2W27-SB2. However, during this period both single and multi bedrooms did not meet the CIBSE night time criterion. At the same time, these spaces did not meet BSEN15251 Cat I criterion except 2W27-SB1. However, if the monitored results are

considered within an annual perspective while assuming that the overheating does not occur outside May to September period, the bedrooms could meet BSEN15251 Cat I criterion³³.

Generally Wards 27 and 32 showed a nighttime overheating trend. This will have a significant negative impact on the patient sleeping ability [1]. The model calibration showed this could be avoided to a great extent if the single bedroom doors are kept open while windows in both single and multi-occupancy bedrooms are opened to enhance the cross ventilation across the ward i.e. multibedroom doors are opened all the time and if the single bedroom doors are kept open, these wards could move towards an open ward character. In reality, the single bedroom doors were kept closed most of the time. Furthermore, some parts of the internal courtyards are being converted into additional ward/clinical spaces. This development, common in many UK Nucleus-type hospitals and driven by a wish to maintain adjacencies between medical functions, is resulting in deep plan buildings and diminishing the prospects of cross ventilation. However, in such situations, at Glenfield Hospital, night-time overheating could be reduced by increasing the night-time mechanical ventilation rate marginally (say by 0.5 ach⁻¹). The applicability of this short term action is demonstrated in the 2010 enhanced ventilation model (Appendix A). But, if the courtyards are filled substantially then the mechanical ventilation rate need to be higher than 3 ach⁻¹ to achieve reasonable comfort conditions. This will have major impact on energy consumption, especially electrical energy, and CO₂ emissions [3]. The DeDeRHECC research team will be investigating the impact of courtyard filling in more detail in future research.

The monitoring results also indicate that reasonably good comfort conditions could be achieved with a mechanical ventilation rate as low as 1 ach⁻¹ when there is adequate provisions for window opening. The HTM03-01-prescribed 6 ach⁻¹ may not be necessary to create comfortable conditions in Leicester. Our previous research work on Bradford also

³³ Spaces were monitored for four months out of five summer months.

1 demonstrated a similar finding [2]. Generally in the Midlands, northern England and Scotland,
2 hospitals could achieve comfortable conditions by combining natural ventilation with a low
3 level of mechanical ventilation. In this scenario, the mechanical ventilation will primarily
4 improve the quality of the indoor air rather than creating comfort. Such a strategy could
5 contribute to huge reductions in CO₂ emissions.
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11 The predictions were made assuming that ventilation rates are the same as at the
12 commissioning³⁴ stage for current and future. However, the plant and the system are 20 years
13 old and there could be some loss in the ventilation rate due to leakages in the ducting system
14 and reduction in fan efficiency. In order to picture this uncertainty the space was modelled
15 with 0.8 ach⁻¹ (85 l/s) as part of the calibration work. The results of this exercise show that
16 the maximum temperatures³⁵ of the spaces for summer 2010 were similar to that of the 135
17 l/s model (Table 4) for the same period. Furthermore, except for the nurse station, all the
18 spaces met the HTM03-01 threshold³⁶. Therefore, results presented in the Table 6 should be
19 viewed taking into account this uncertainty. The DeDeRHECC research team is currently
20 making efforts to monitor the ventilations rates accurately.
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38 The predictions for Ward 27 show that light-touch low carbon interventions could have a
39 positive impact on indoor comfort conditions in hospital wards where the impact of climate
40 change is not severe. The predictions also indicate that internal and solar gains play a major
41 role in overheating the ward spaces with a low level of mechanical ventilation. To a large
42 extent the overheating could be avoided through proper management/storage of heat radiating
43 equipment and shading windows adequately. Especially during extreme years, appropriate
44 shading could reduce the overheating hours substantially [3]. Further, improvements could
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56 ³⁴ In 1989 the ventilation rate was 135 l/s for the area under study.

57 ³⁵ The maximum temperature of 2W27-SB1, 2W27-SB2, 2W27-6MB1, 2W27-6MB2, 2W27-NS and 2W27-CD
58 were 28.5 °C, 28.5 °C, 29.5 °C, 29.2 °C, 29.8 °C and 28.5 °C respectively.

59 ³⁶ The hours over 28.0 in 2W27-SB1, 2W27-SB2, 2W27-6MB1, 2W27-6MB2, 2W27-NS and 2W27-CD were
60 10, 8, 35, 18, 103 and 13 respectively.
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1 be made if the restrictions on window opening were relaxed, perhaps with the provision of an
2 appropriate ‘guard’ for patient safety [2], or if louvred panels, separate from the windows,
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4 were used for ventilation. On the other hand, for the current and future Midland climate, the
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6 impact of a slow-rotating fan on reducing the overheating hours in hospital wards is
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8 substantial. Furthermore, fans are a low energy and low cost approach to reducing
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10 overheating hours in hospitals [1].
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18 **8. Conclusion**

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22 The paper has summarised the performance of selected wards and the waiting area at
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24 Glenfield Hospital. These spaces, representative within the context of the whole building, and
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26 examples of spaces within a ‘type’ hospital building of which there are more than 100
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28 examples in the UK, were monitored during June to September 2010. Virtually all the spaces
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30 operated within the limit of reasonable comfort conditions. The major deviation from the
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32 comfort criteria was observed in the incidence of night-time overheating.
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38 The multi-zone model was sensitive to internal gains, and the degree and duration of window
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40 and door opening. For the calibration period, the predicted results of the model show good
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42 agreement with measured maximum and mean temperatures, and the HTM03-01 threshold.
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44 The study also demonstrates the difficulty in calibrating a multi-zone hospital model,
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46 especially when there are regular variations in occupancy level, internal gains etc.
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51 Three sequential interventions show that the overheating could be controlled into the 2050s
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53 for both typical and extreme years through light touch low carbon interventions. Beyond
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55 2050 these light touch measures may not work and more fundamental interventions may be
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57 required.
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Table 1: Criteria for assessing internal temperatures in naturally ventilated spaces [3].

Assessment metric	Source	Criterion	Applicability	Comment
Total hours, dry-bulb temperature over 28°C.	HTM03-01 (2007)	Limiting value 50 hours.	All spaces and buildings.	Weather year to be used in simulations not stated.
Night time hours operative temperature over 26°C.	CIBSE Guide A (1999)	No more than 1% of hours above value.	Sleeping spaces only.	Value based on homes and not health care facilities.
Adaptive comfort Cat. I and Cat II envelopes. Thresholds of operative temperature vary with running mean of ambient temperature.	BSEN15251 (2008)	No more than 5% of hours outside envelope, in any day, week, month or year.	Naturally ventilated buildings with operable windows.	Cat I is applicable to spaces with vulnerable individuals, such as wards, Cat II for ‘normally’ occupied spaces, such as offices, consulting rooms, etc.

Notes

1. The limiting value for a year is 50, 37 (night time) and 438 hours for HTM03-01, CIBSE and BSEN15251 respectively.

Table 2: Comparison of internal temperatures measured between 1st June and 30th September, 2010, with BSEN15251, CIBSE and HTM03 overheating criteria: Glenfield Hospital.

Space	Space reference	Maximum temp °C (24 hours)	Minimum temp °C (24 hours)	Mean daytime temp °C (7:00 to 20:00)	Mean night time temp °C (21:00 to 6:00)	Maximum diurnal range (K)	Hours over 25 °C (24 hours)	HTM03: Hours over 28 °C (24 hours)	Hours over 24 °C (21:00 to 6:00)	CIBSE: Hours over 26 °C (21:00 to 6:00)	BSEN15251: Hours over Cat I / Cat II upper
Main Waiting area (WA)	1WA	26.9	20.2	23.9	24.1	3.6	442	0	678	NA	13/0
Ward 18, level 1											
Open ward (OW), 22 beds	1W18-22OW	26.6	20.0	23.8	23.3	4.3	182	0	243	0	45/1
Nurse station(NS)	1W18-NS	28.9	21.4	25.4	24.7	4.3	1617	2	1017	NA	462/ 103
Ward 19, level 1											
Open ward (OW), 24 beds	1W19-24OW	26.8	20.3	23.8	23.5	4.3	284	0	330	2	106/2
Nurse station (NS)	1W19-NS	27.8	22.1	24.2	24.0	3.8	290	0	625	NA	86/0
Ward 27, level 2											
Corridor (CD)	2W27-CD	27.7	21.5	24.5	24.3	3.9	770	0	769	NA	NA
Multi bedroom 1 (MB1), 6beds	2W27-6MB1	28.4	20.5	24.7	24.6	6.2	1050	7	859	110	255/ 60
Single bedroom 1 (SB1)	2W27-SB1	27.3	19.6	24.1	23.9	3.7	406	0	384	35	59/ 02
Single bedroom 2 (SB2)	2W27-SB2	29.3	18.2	23.9	23.7	5.0	455	70	348	112	206/ 102
Nurse station (NS)	2W27-NS	29.0	22.5	25.2	25.0	4.2	1419	57	936	NA	NA
Ward 32, level 2											
Corridor (CD)	2W32-CD	28.0	21.9	24.5	24.2	3.8	718	2	712	NA	NA
Multi bedroom 1 (MB1), 4 beds	2W32-4MB1	28.3	22.2	25.1	24.8	3.2	1326	6	950	158	244/ 33
Multi bedroom 2 (MB2), 4 beds	2W32-4MB2	28.0	21.5	24.8	24.6	3.8	997	0	906	94	166/ 8
Multi bedroom 3 (MB3), 4beds	2W32-4MB3	28.6	20.5	25.2	25.0	4.8	1547	14	1049	187	397/ 58
Single bedroom 1 (SB1)	2W32-SB1	28.3	21.0	24.5	24.4	2.8	838	4	712	177	253/ 39
Single bedroom 2 (SB2)	2W32-SB2	28.6	20.5	24.7	24.7	3.2	1017	26	885	193	280/ 60
Nurse station (NS)	2W32-NS	28.0	21.9	24.8	24.5	3.9	1062	1	889	NA	NA

Notes (Table 2):

1. Total number of hours: 2928. Total number of night time (21:00 to 6:00) hours: 1220
2. For the space 2W27-SB1, the monitored data is available for 2247 hours which includes 937 night time hours. Error in data after 2nd September 14:00 hrs.
3. The space 2W27-6MB2 not monitored.
4. The limiting overheating values for the monitored period are: HTM03, 40 hours over 28 °C; BSEN15251, 147 hours above category upper threshold and CIBSE, 12 night time hours over 26°C.
5. For the space 2W27-SB1, the limiting overheating values are: HTM03, 31 hours over 28 °C; BSEN15251, 113 hours above category upper threshold and CIBSE, 10 night time hours over 26°C.
6. CIBSE night time condition is not applicable to nurse station corridors and waiting area since there is no provision for sleeping in these spaces.
7. BSEN15251 conditions are applicable only to spaces with operable windows. Nurse station in open wards (OW) benefit from operable windows since they are open islands in the wards.
8. Bold and italic values with grey shade: criterion limit exceeded

Table 3: Model characteristics.

Description	2W27-SB1	2W27-SB2	2W27-MB1	2W27-MB2	2W27-NS	2W27-CD
External wall area (m ²)	13.2	13.2	18.2	37.4	NA	NA
Floor area (m ²)	14.6	14.6	49.0	49.0	18.2	45.6
Volume (m ³)	39.5	39.5	132.3	132.3	49.1	115.0
Window area (m ²)	2.2	2.2	5.8	8.6	NA	NA
Internal heat gain (W/m ²)	5.4 to 15.1	5.4 to 15.1	8.6 to 19.6	8.6 to 19.6	54 to 65	0.7 to 4.4
Perimeter heating	Yes	Yes	Yes	Yes	NO	NO
Window opening strategy	The occupants were assumed to open the windows. The maximum opening is 100mm. The opening area assumed to be 0% if the $T_{out} \leq 10^{\circ}\text{C}$, and 50% if $T_{out} > 10^{\circ}\text{C}$ and $T_{in} \leq 18^{\circ}\text{C}$, then ramps up to 100% at $T_{in} \geq 20^{\circ}\text{C}$				NA	NA
Perimeter heating regime	Set point temperature is 23°C. Set point is 100% at $T_{out} \leq -3^{\circ}\text{C}$ and it ramps down to 80% at $T_{out} = 16^{\circ}\text{C}$. It is off at $T_{out} = 20^{\circ}\text{C}$.				NA	NA
Ventilation heating regime	Continuous supply of fresh air at the rate of 135 l/s for the area under study. There is only one supply grille and it is located on the nurse station ceiling. Supply air is heated to 18°C. Set-point ramped down from 100% at $T_{out} \leq 16^{\circ}\text{C}$ to zero at $T_{out} \geq 18^{\circ}\text{C}$.					
Extract regime	There are four toilets in this area. Each toilet has the facility to extract 25 l/s continuously. The balance supplied air (35 l/s) escapes through windows.					

Table 4: Comparison of measured and predicted results of ward 27 for the calibration period.

Space reference		Max. temp (°C)	Min. temp (°C)	Mean night time temp (°C)	HTM03: Total hours over 28°C	CIBSE: Night time hours over 26°C	BSEN15251: Total hours above Cat I upper limit	BSEN15251: Total hours above Cat II upper limit
2W27-SB1	Measured	27.3	19.6	23.9	0	35	59	2
	Predicted	28.3	22.7	23.5	4	24	61	3
2W27-6MB1	Measured	28.4	20.5	24.6	6	98	305	71
	Predicted	28.9	23.0	23.8	16	51	163	52
2W27-NS	Measured	29.0	22.5	25.0	57	NA	NA	NA
	Predicted	29.4	24.3	25.1	49	NA	NA	NA

Notes (Table 4):

1. Calibration period for MB1 and NS is 1st June to 30th September 2010.
2. Calibration period for SB1 is 1st June to 2nd September 2010.

Table 5: Summary of predicted performance of Ward 27 during the summer of 2010.

Space reference	Max. temp (°C)	Min. temp (°C)	Mean night time temp (°C)	HTM03: Total hours over 28°C	CIBSE: Night time hours over 26°C	BSEN15251: Total hours above Cat I upper limit	BSEN15251: Total hours above Cat II upper limit
2W27-SB1	28.1	22.9	23.5	4	25	148	20
2W27-SB2	28.1	22.9	23.4	4	22	140	17
2W27-6MB1	29.1	22.9	23.8	18	55	289	94
2W27-6MB2	29.0	22.8	23.5	11	32	265	89
2W27-NS	29.4	24.7	25.4	53	NA	NA	NA
2W27-CD	28.1	23.1	23.8	3	NA	NA	NA

Notes (Table 5):

1. The HTM03 threshold is based on dry bulb temperature and rest are based on dry resultant temperature.
2. CIBSE night time condition is not applicable to nurse station and corridors since there is no provision for sleeping.
3. BSEN15251 conditions are applicable only to spaces with operable windows.
4. It is assumed that during the period of October to April the spaces will not overheat due to elevated ambient temperature and solar gains. Therefore the limiting overheating values are: HTM03, 50 hours over 28 °C; BSEN15251, 438 hours above category upper threshold and CIBSE, 37 night time hours over 26°C.

Table 6: Summary of predicted performance of ward 27 for current and future, test reference (TRY) and design summer (DSY) years.

Scenario	Space reference	Year	Max. temp (°C)		Min. temp (°C)		Mean night time temp (°C)		HTM03: Total hours over 28°C		CIBSE: Night time hours over 26°C		BSEN15251: Total hours above Cat I upper limit		BSEN15251: Total hours above Cat II upper limit	
			TRY	DSY	TRY	DSY	TRY	DSY	TRY	DSY	TRY	DSY	TRY	DSY	TRY	DSY
Existing	2W27-SB1	05	27.5	28.4	22.8	22.7	23.4	23.5	0	7	10	30	154	108	4	6
		30s	28.9	31.6	22.6	22.8	23.9	25.3	26	559	72	557	257	870	56	334
		50s	30.8	33.2	22.7	22.6	24.5	26.0	168	935	225	745	556	1224	129	631
	2W27-6MB1	05	29.2	30.5	22.9	22.9	23.9	23.9	19	40	53	81	387	255	119	65
		30s	30.5	32.5	22.9	23.0	24.4	25.9	80	775	167	707	469	1129	169	602
		50s	32.1	34.2	22.9	22.9	25.2	26.7	348	1147	424	893	897	1514	421	879
	2W27-NS	05	29.3	30.5	24.8	24.7	25.5	25.5	49	78	NA	NA	NA	NA	NA	NA
		30s	30.6	33.2	24.8	24.8	26.0	27.4	180	1254	NA	NA	NA	NA	NA	NA
		50s	32.5	34.8	24.8	24.7	26.7	28.2	595	1662	NA	NA	NA	NA	NA	NA
	2W27-SB1	05	27.1	28.1	22.6	22.6	23.3	23.4	0	3	4	17	73	36	2	0
		30s	28.6	31.1	22.5	22.7	23.7	24.9	11	393	31	433	110	562	25	175
		50s	30.1	32.6	22.5	22.5	24.2	25.6	97	740	158	610	280	868	69	365
Stage 1: low internal gain plus existing	2W27-6MB1	05	28.7	30.0	22.9	22.9	23.6	23.6	6	18	24	46	252	153	57	42
		30s	29.9	32.1	22.9	22.9	24.0	25.4	43	557	78	571	303	804	101	404
		50s	31.4	33.7	22.9	22.9	24.7	26.1	215	908	266	777	623	1125	243	598
	2W27-NS	05	28.2	29.4	23.9	23.9	24.6	24.6	6	26	NA	NA	NA	NA	NA	NA
		30s	29.4	31.9	23.9	23.9	25.0	26.3	52	748	NA	NA	NA	NA	NA	NA
		50s	31.1	33.6	23.9	23.9	25.6	27.0	292	1140	NA	NA	NA	NA	NA	NA
	2W27-SB1	05	26.3	27.8	22.3	22.4	23.2	23.2	0	1	0	9	16	10	0	0
		30s	28.2	30.4	22.4	22.5	23.4	24.5	4	232	12	303	33	226	4	62
		50s	28.9	31.9	22.3	22.3	23.9	25.2	38	503	102	477	88	452	19	130
	2W27-6MB1	05	27.8	29.1	22.9	22.9	23.4	23.5	0	6	4	20	89	59	6	11
		30s	28.8	31.3	22.9	22.9	23.8	25.0	9	357	33	461	130	483	29	187
		50s	30.1	33.1	22.9	22.9	24.3	25.7	98	671	176	612	285	741	70	312
Stage 2: Horizontal shading plus option 1	2W27-NS	05	27.5	28.8	23.9	23.9	24.4	24.4	0	10	NA	NA	NA	NA	NA	NA
		30s	28.8	31.4	23.9	23.9	24.7	25.9	16	526	NA	NA	NA	NA	NA	NA
		50s	30.1	33.0	23.9	23.9	25.2	26.6	163	907	NA	NA	NA	NA	NA	NA
Stage 3: Fan: active above 26°C plus option 2	2W27-SB1	05	26.0	26.6	22.3	22.4	23.2	23.2	NA	NA	0	0	14	1	0	0
		30s	27.0	29.2	22.4	22.5	23.4	24.3	NA	NA	1	123	15	48	0	5
		50s	27.7	30.7	22.3	22.3	27.4	24.8	NA	NA	22	290	17	104	0	26
	2W27-6MB1	05	26.6	27.9	22.9	22.9	23.4	23.5	NA	NA	0	6	58	26	4	1
		30s	27.6	30.1	22.9	22.9	23.7	24.6	NA	NA	4	204	56	152	4	28
		50s	28.9	31.9	22.9	22.9	24.2	25.2	NA	NA	67	380	85	257	10	88
	2W27-NS	05	26.3	27.6	23.9	23.9	24.4	24.4	NA	NA	NA	NA	NA	NA	NA	NA
		30s	27.6	30.2	23.9	23.9	24.6	25.4	NA	NA	NA	NA	NA	NA	NA	NA
		50s	28.9	31.8	23.9	23.9	25.0	25.9	NA	NA	NA	NA	NA	NA	NA	NA

Notes (Table 6):

1. 05, 30s and 50s represent 2005 (current) and 2030s and 2050s respectively.
2. The HTM03 threshold is based on dry bulb temperature and rest are based on dry resultant temperature.
3. CIBSE night time condition is not applicable to nurse station and corridors since there is no provision for sleeping in these spaces.
4. BSEN15251 conditions are applicable only to spaces with operable windows.
5. HTM03 standard not applicable for fans.
6. Night time hours are 21:00 to 6:00.
7. Simulated hours (3672) are for May to September.
8. It is assumed that during the period of October to April the spaces will not overheat due to elevated ambient temperature and solar gains. Therefore the limiting overheating values are: HTM03, 50 hours over 28 °C; BSEN15251, 438 hours above category upper threshold and CIBSE, 37 night time hours over 26°C.
9. Un-shaded values indicate that they are within the threshold limit, dark grey shade indicate that the exceedance is substantial, and light grey shade indicates exceedance is minor.

Appendix A: Summary of predicted performance of Ward 27 during the summer of 2010 with additional air supply.

Space	Max. temp (°C)	Min. temp (°C)	Mean night time temp (°C)	HTM03: Total hours over 28°C	CIBSE: Night time hours over 26°C	BSEN15251: Total hours above Cat I upper limit	BSEN15251: Total hours above Cat II upper limit
2W27-SB1	27.8	22.9	23.4	0	18	105	12
2W27-SB2	27.7	22.9	23.4	0	14	98	10
2W27-6MB1	28.8	22.9	23.5	10	29	206	59
2W27-6MB2	28.7	22.8	23.4	5	19	199	61
2W27-NS	29.0	24.4	25.0	19	NA	NA	NA
2W27-CD	27.8	22.8	23.3	0	NA	NA	NA

Notes (Appendix A):

1. The HTM03 threshold is based on dry bulb temperature and rest are based on dry resultant temperature.
2. CIBSE night time condition is not applicable to nurse station and corridors since there is no provision for sleeping
3. BSEN15251 conditions are applicable only to spaces with operable windows.

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Fig. 16: Measured and predicted temperature in 2W27-MB1, external temperature, and solar radiation intensity for calibration period.

Figure(s)

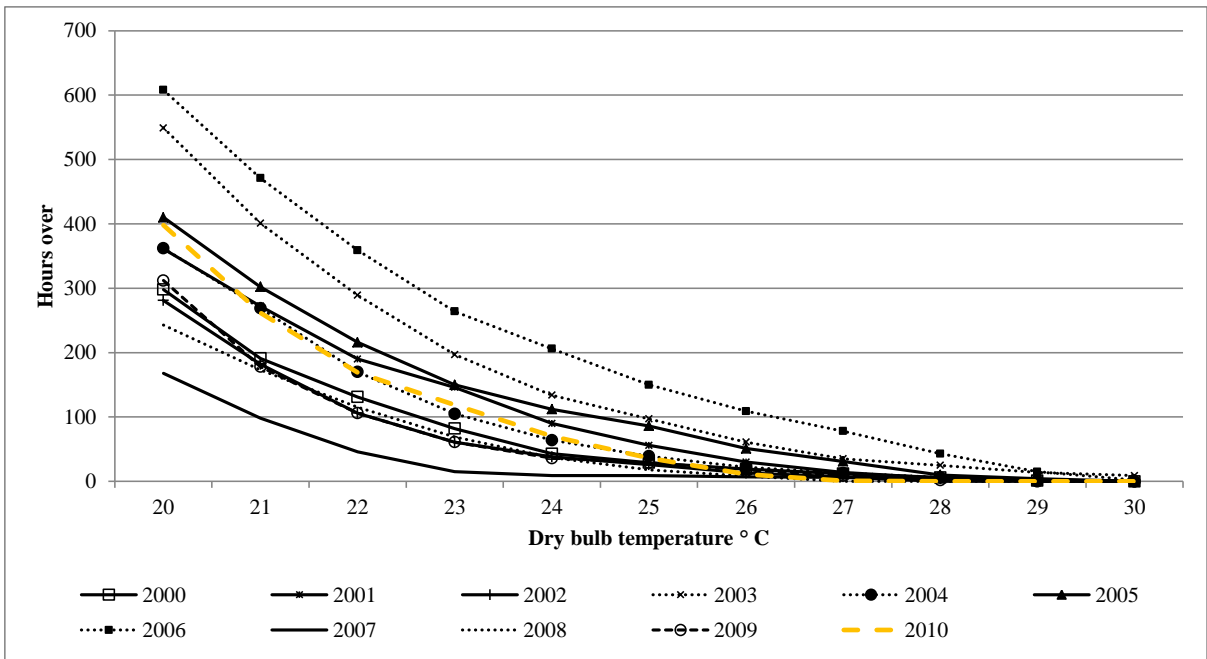


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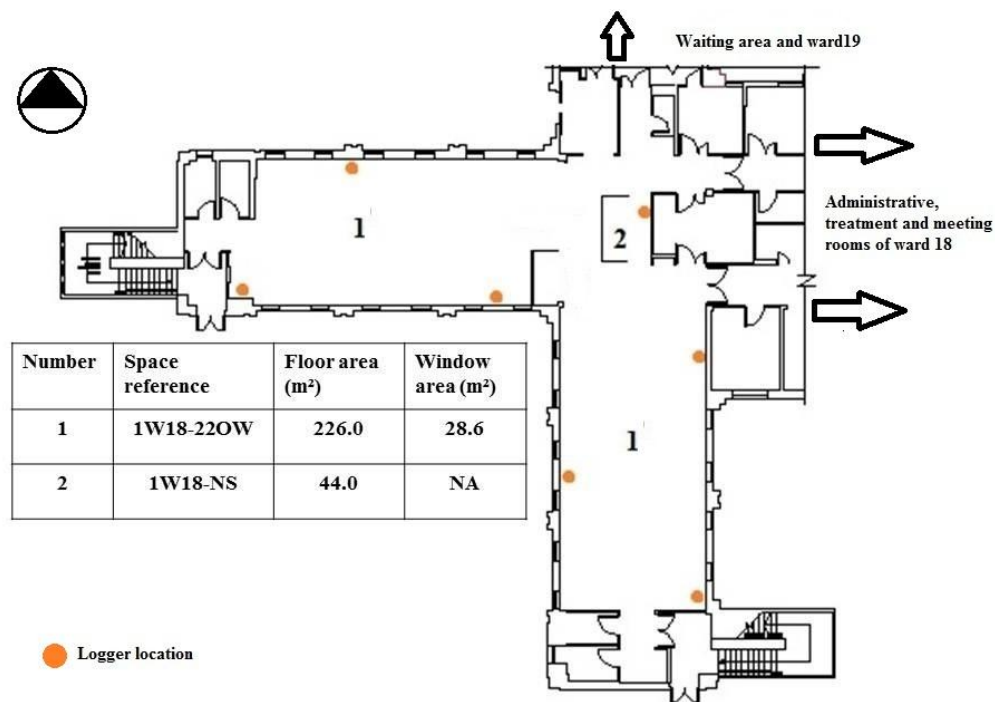


Fig. 3: Logger locations in ward 18 on ground floor. The open ward (OW) houses 22 beds.

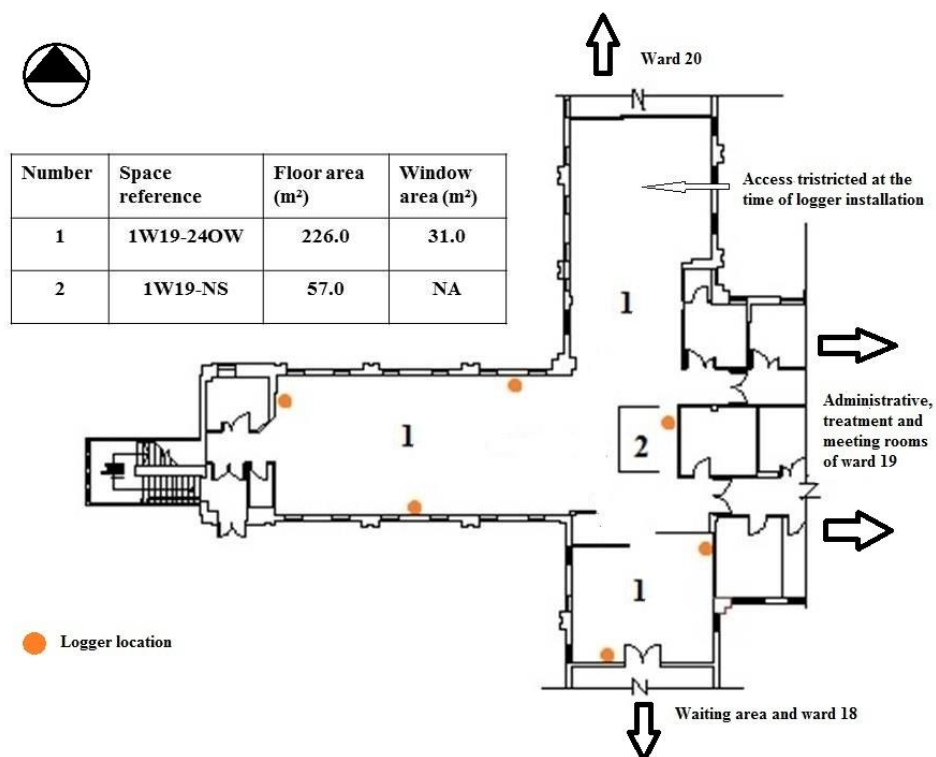


Fig. 4: Logger locations in ward 19 on ground floor. The open ward (OW) houses 24 beds.

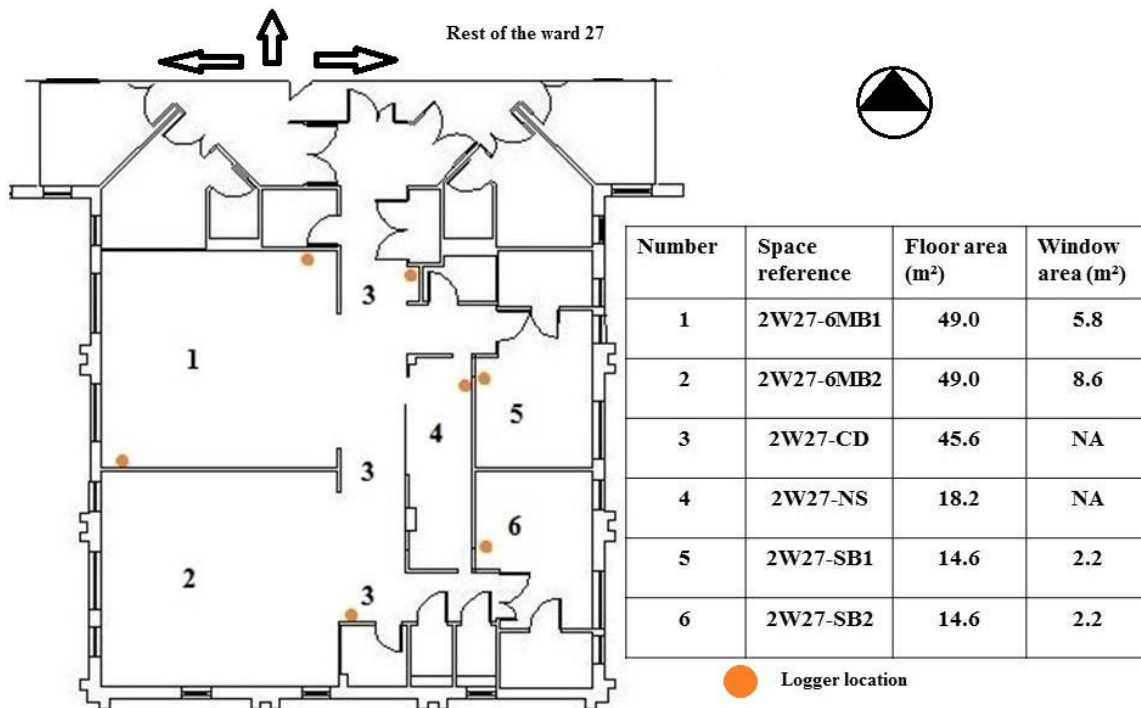


Fig. 5: Logger locations in ward 27 on the first floor. The multibed (MB) room 1 and 2 have 6 beds, room 5 and 6 have single beds.

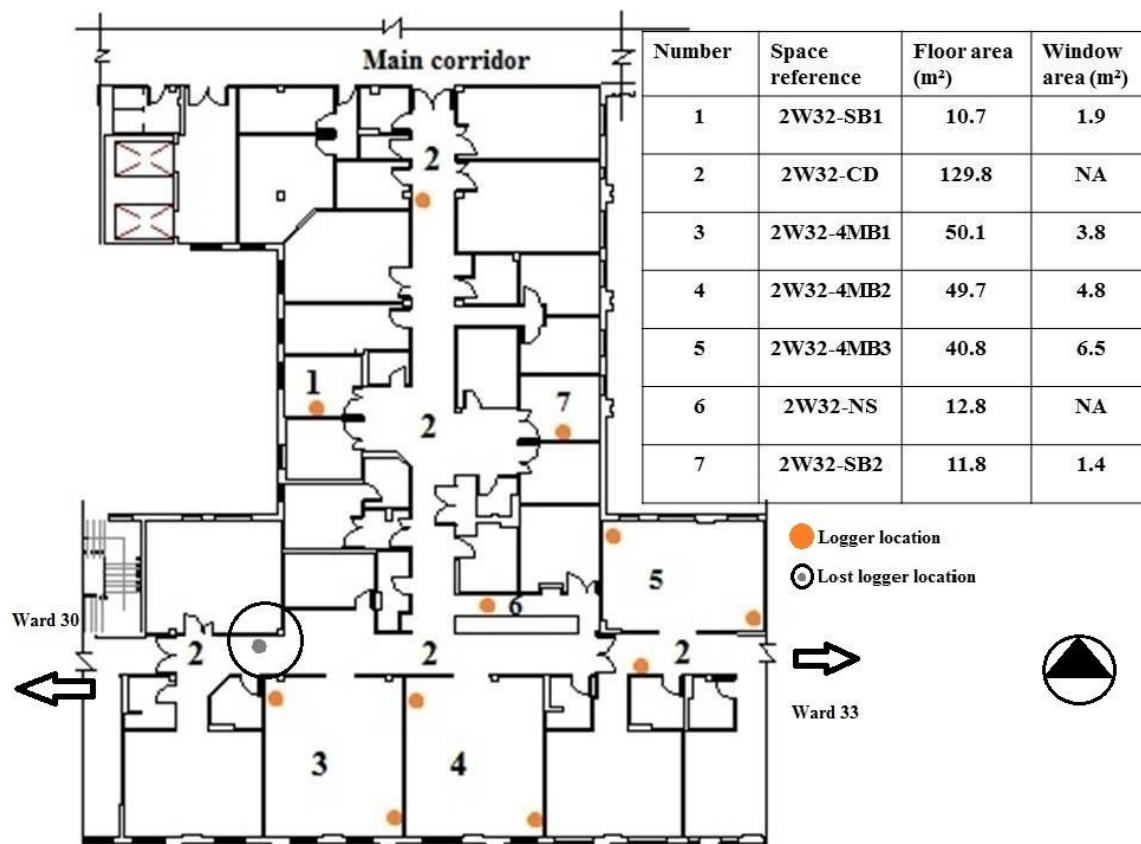


Fig. 6: Logger locations in ward 32 on the first floor. The multibed (MB) rooms, 3 to 5 have 4 beds, rooms 1 and 7 have single beds.

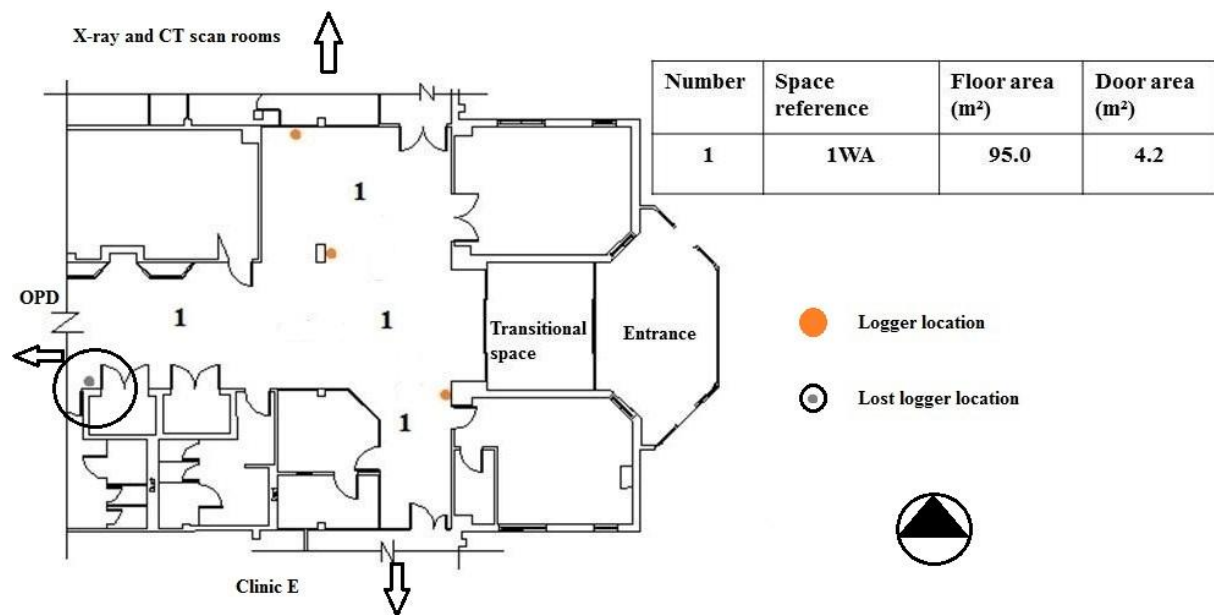


Fig. 7: Logger locations in waiting area (WA).

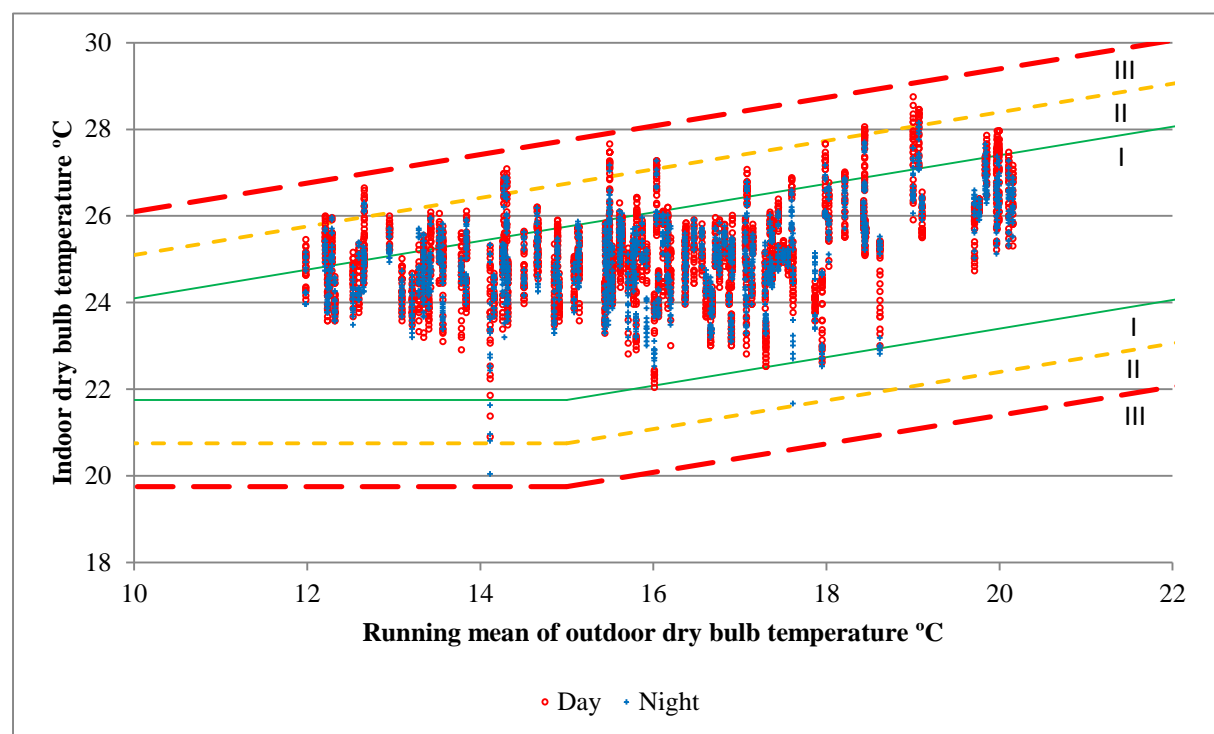


Fig. 8: Internal temperatures of 2W32-4MB3 compared to BSEN15251 category limits.

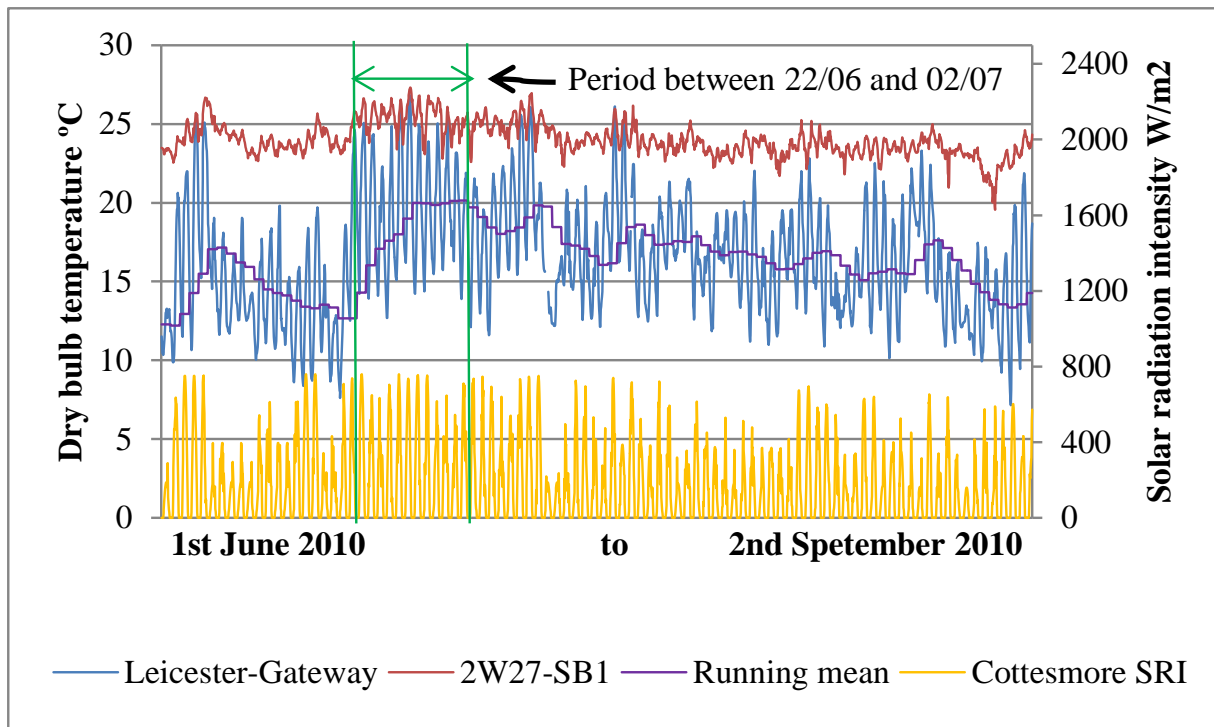


Fig.9: Internal temperature in W27-SB1, external temperature, its running mean and solar radiation intensity.

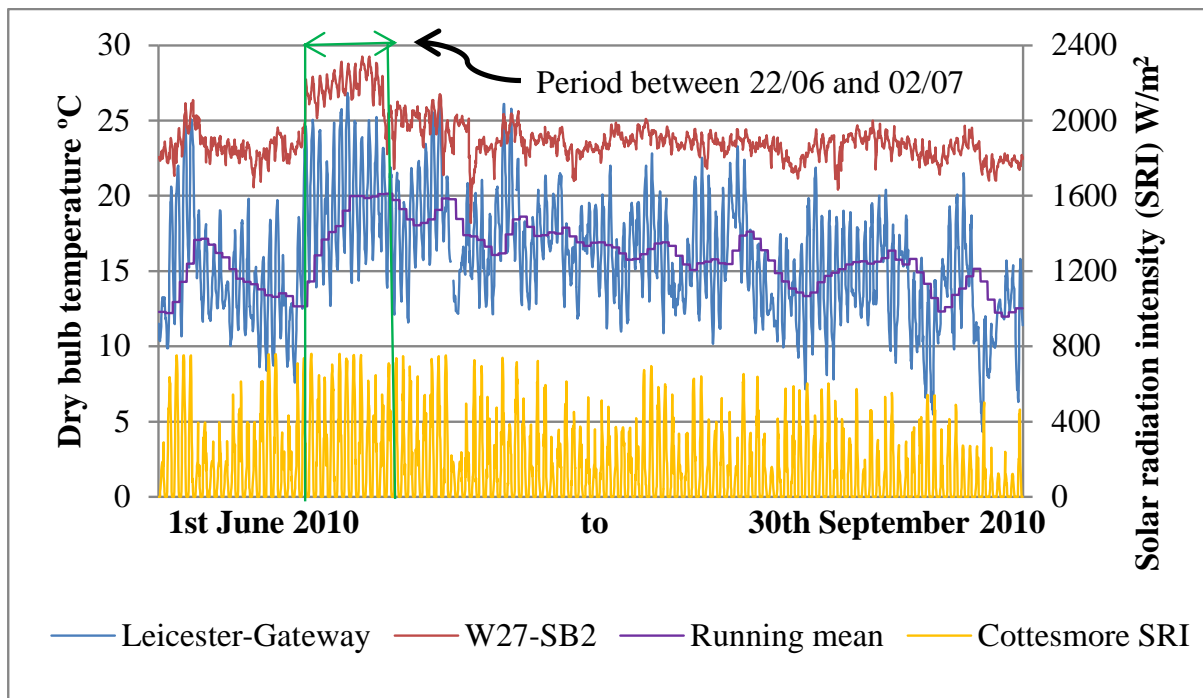
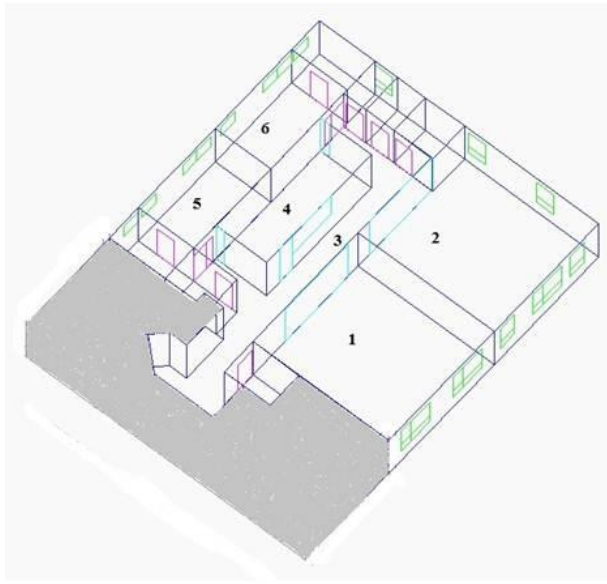


Fig.10: Internal temperature in W27-SB2, external temperature, its running mean and solar radiation intensity.



Number	Space reference	Floor area (m ²)	Window area (m ²)
1	2W27-6MB1	49.0	5.8
2	2W27-6MB2	49.0	8.6
3	2W27-CD	45.6	NA
4	2W27-NS	18.2	NA
5	2W27-SB1	14.6	2.2
6	2W27-SB2	14.6	2.2

Fig.11: Multi zone model of ward 27.

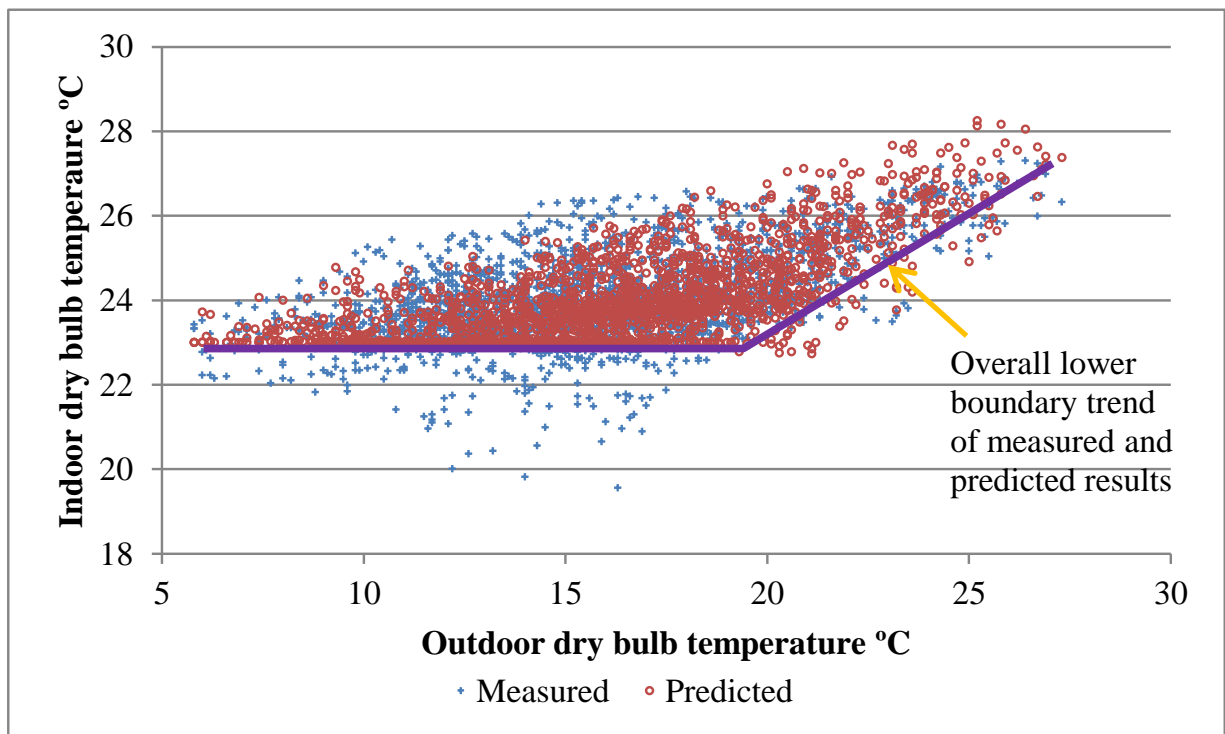


Fig. 12: W27-SB1, measured and predicted temperature.

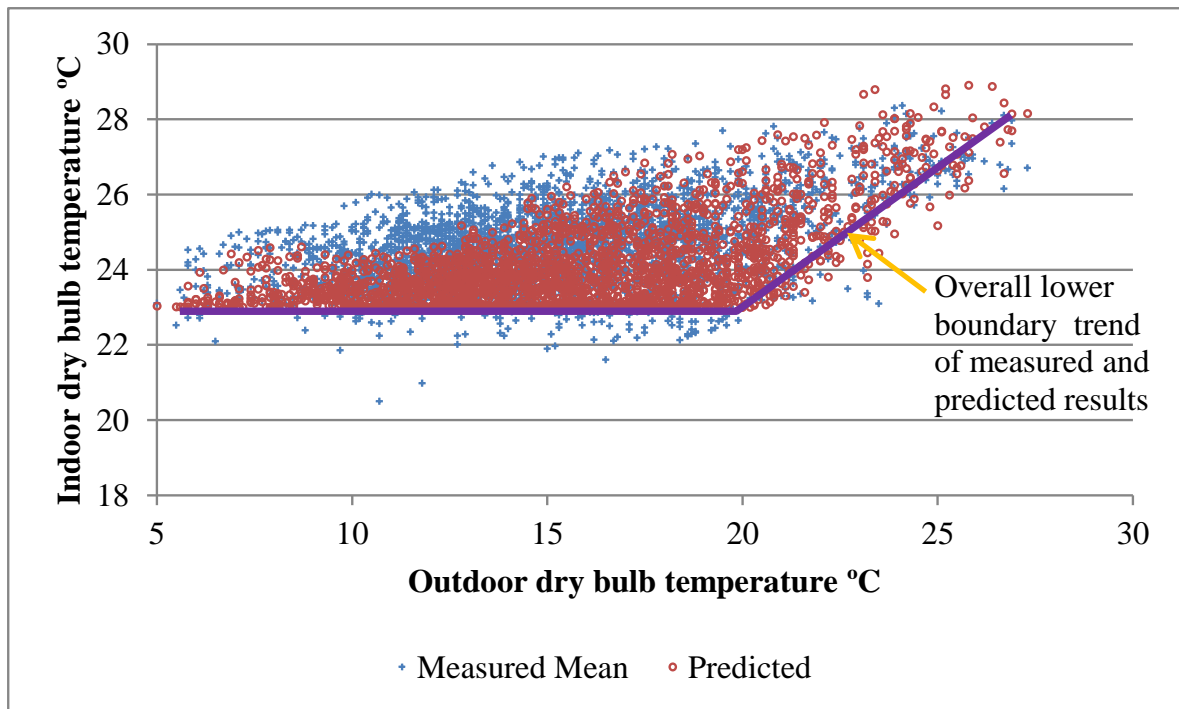


Fig. 13: W27-MB1, measured and predicted temperature.

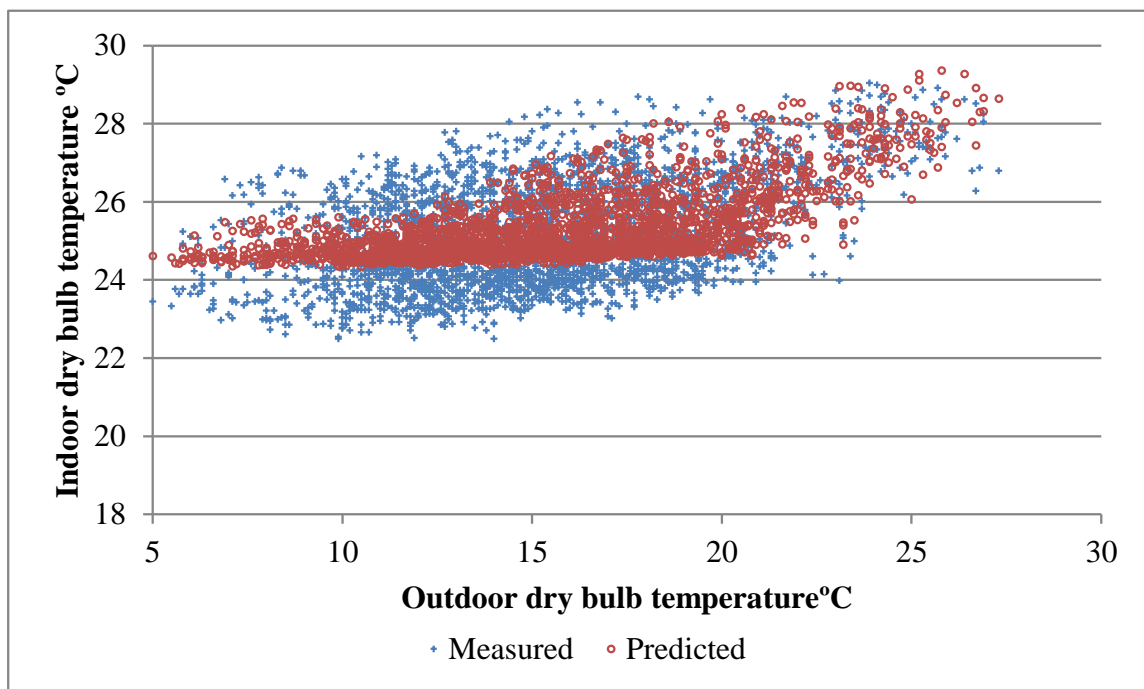


Fig. 14: W27-NS, measured and predicted temperature.

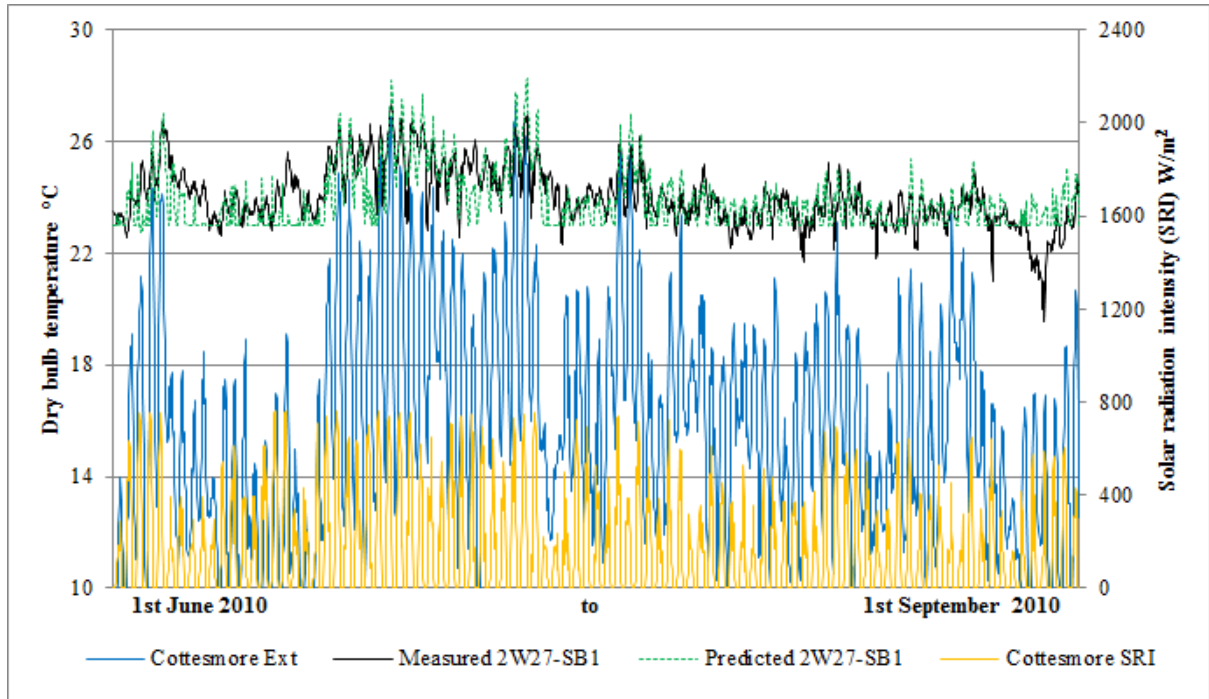


Fig. 15: Measured and predicted temperature in 2W27-SB1, external temperature, and solar radiation intensity for calibration period.

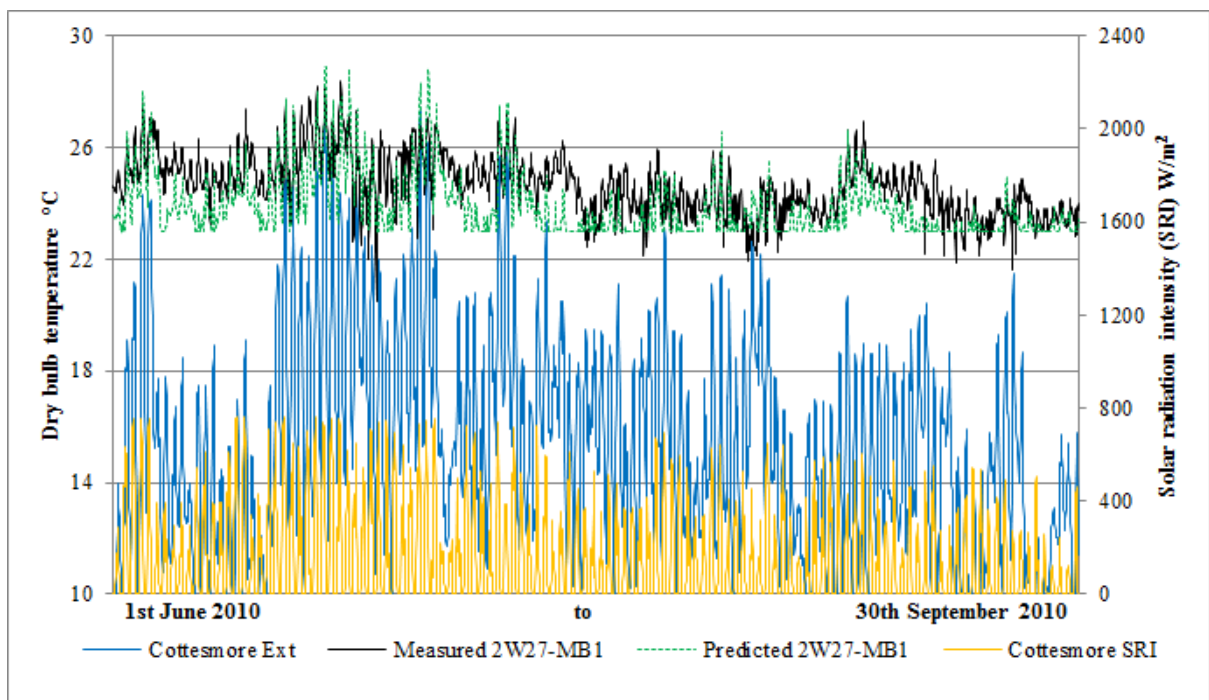


Fig. 16: Measured and predicted temperature in 2W27-MB1, external temperature, and solar radiation intensity for calibration period.

Highlights

Glenfield Hospital comprises connected cruciform blocks with numerous small courtyards between. The hospital has mechanical ventilation and perimeter heating. The wards have a hybrid ventilation strategy with a low rate of mechanical ventilation. Ventilation through windows is the main source of summer time cooling. This paper investigates the summer time performance of spaces that are mechanically ventilated but passively cooled during summer. The paper presents the measured indoor temperatures in selected hospital spaces and compares them with thermal comfort criteria. Finally, future summer conditions for a typical ward space are predicted using a calibrated dynamic thermal model.